



Farhadi Beldachi, A., Anastasopoulos, M., Manolopoulos, A., Tzanakaki, A., Nejabati, R., & Simeonidou, D. (2020). Resilient Cloud-RANs Adopting Network Coding. In *Optical Network Design and Modeling: 23rd IFIP WG 6.10 International Conference, ONDM 2019, Athens, Greece, May 13–16, 2019, Proceedings* (pp. 349-361). (Lecture Notes in Computer Science). Springer, Cham.  
[https://doi.org/10.1007/978-3-030-38085-4\\_30](https://doi.org/10.1007/978-3-030-38085-4_30)

Peer reviewed version

Link to published version (if available):  
[10.1007/978-3-030-38085-4\\_30](https://doi.org/10.1007/978-3-030-38085-4_30)

[Link to publication record in Explore Bristol Research](#)  
PDF-document

This is the author accepted manuscript (AAM). The final published version (version of record) is available online via Springer Nature at [https://link.springer.com/chapter/10.1007/978-3-030-38085-4\\_30](https://link.springer.com/chapter/10.1007/978-3-030-38085-4_30). Please refer to any applicable terms of use of the publisher.

## University of Bristol - Explore Bristol Research

### General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:  
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

# Resilient Cloud-RANs Adopting Network Coding

Arash Farhadi Beldachi<sup>(1)</sup>, Markos Anastasopoulos<sup>(1)</sup>, Alexandros Manolopoulos<sup>(2)</sup>, Anna Tzanakaki<sup>(1)(2)</sup>, Reja Nejabati<sup>(1)</sup> and Dimitra Simeondou<sup>(1)</sup>

(1) High Performance Networks Group, University of Bristol, UK

(2) Department of Physics, University of Athens, Greece

**Abstract.** This study focuses on the provisioning of resilient Cloud Radio Access Network (C-RAN) services employing optical transport networks. In response to the high bandwidth requirements necessary for the protection of the C-RAN architecture from optical transport network and/or BBU failures, a novel approach based on Network Coding (NC) is proposed. A novel architectural and hardware framework to enable NC are also provided and a suitable implementation addressing the problem of fast NC-related operations processing at the edge is demonstrated. A global time stamping solution that can be used to address the strict synchronization requirements of FH flows arriving at the BBUs, keeping buffering at the edge as low as possible, has been developed. The performance of the proposed solution has been experimentally evaluated demonstrating negligible penalties. Network level modeling results demonstrate a reduction of the total optical network capacity required for this type of applications by 33%.

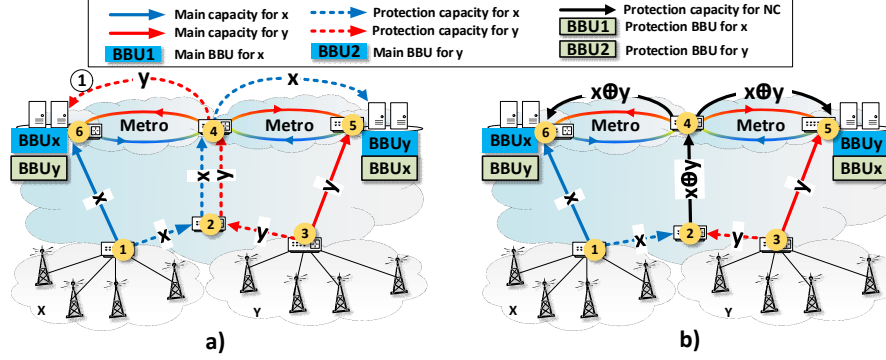
**Keywords:** First Keyword, Second Keyword, Third Keyword.

## 1 Introduction

Cloud-Radio Access Networks (C-RANs) have been recently proposed as a key concept to address the inefficiencies of traditional RAN systems and support services requiring very low latency, high reliability, density and mobility. In C-RAN, Remote Units (RUs), are connected to the Central Unit (CU) where the Baseband Unit (BBU) pool is located through high bandwidth transport links, transmitting I/Q streams, known as fronthaul (FH) [1]. Through its pooling and coordination gains, C-RAN addresses the increased capital and operational costs, as well as the limited scalability and flexibility of traditional RAN. However, C-RAN requires tremendous transport bandwidth and impose strict latency and synchronization constraints [1]-[2]. To address the need for a flexible transport network offering the required capacity levels we have proposed the Time-Shared Optical Network (TSO) solution [1]. However, the transport capacity problem is further exaggerated under survivable C-RAN deployments (see i.e. [3]-[8]). In many protection schemes, the optical network capacity is duplicated in size [8] to make possible realistic survivable C-RAN deployments.

A typical example of systems offering protection to any kind of failures (either at the optical transport or the compute domain where BBUs are hosted) is shown in Figure 1a). Specifically, in case of failure of the main paths interconnecting the RUs with the BBUs

(i.e. paths 1-6, 3-5), FH flows are routed to their destination through a set of secondary (protection) paths (1-2-4-5, 3-2-4-6). A similar approach is taken for the C-RAN protection against BBU failures [6]. It is clear that under this scenario, multiple FH flows need to be transferred over a set of links introducing even higher transport bandwidth requirements.



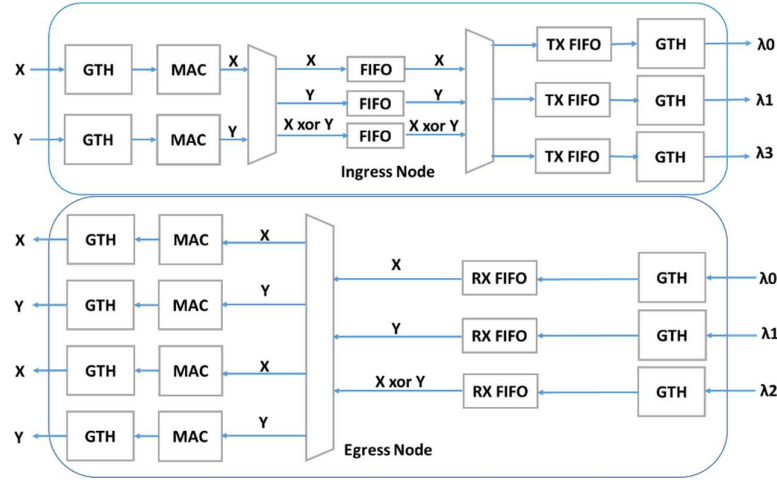
**Figure 1.** Protection of a C-RAN network from failures of compute and/or network elements. a) In the traditional approach, working and protection capacity for regions  $x, y$  are establishes over common links causing bottleneck b) Protection of C-RAN adoting NC. FH flows from regions  $x, y$  are multiplexed ( $x \oplus y$ ) at ingress edge node and replicated at the reducing bandwidth requirmens by half.

To address this issue the concept of Network Coding (NC) [10] is proposed with the aim offer resilient FH services by multiplexing FH flows and therefore reducing the volume of the transmitted I/Q streams. Using NC, 2 different FH traffic streams with the same source and destination nodes are routed through the network following diverse paths. These can be protected through their modulo-two sum that is generated at the source node and forwarded to the common destination node. This allows reconstruction of each one of the two initial streams at the destination node, in case of the occurrence of a failure along one of the two paths that the initial two streams are traversing. This approach offers 1+1 protection capabilities without having to transfer separately the working and protection copies of the two FH streams across the optical transport network. This reduces the overall protection bandwidth requirement by half (see link 2-4 in Figure 1 b). Through this approach, simultaneous protection against optical network and/or compute elements can be achieved.

Although NC has been extensively used to protect networks against link failures, its application in resilient FH networks has not been proposed before. This can be attributed mainly to the overhead that the application of the modulo-two sum and the replication operations of NC introduce in practical systems that may degrade the performance of C-RANs. At the same time, the operation of the decoding process at the edge imposes significant buffering requirements due to the high data rate of FH streams. To address these limitations, we propose the extension of TSON with an architecture and a hardware implementation that manage to execute the coding and decoding processes at line rate. This solution minimises at the same time buffering requirements adopting a purposely developed synchronization scheme to make it suitable for C-RAN implementations. To quantify the benefits of the proposed approach at a network level and further improve

performance, an optimization framework is proposed. The proposed scheme focuses on optimally placing the NC-enabled edge nodes to minimize the overall deployment cost and protect the system from possible network or compute element failures. The performance of the proposed scheme is experimentally validated over the Bristol city test-bed considering the requirements imposed by an operating open source LTE platform.

The rest of the paper is organized as follows: The implementation of the NC enabled edge nodes is provided in Section 2. Section 3 provides a brief description of the resilience 5G network design problem with and without NC considerations. Experimental and theoretical evaluation is carried out in Section 4 whereas Section 5 concludes the paper.



**Figure 2.** Implemented architecture of the TSON technology to solve the 5G network design problem with resilience considerations

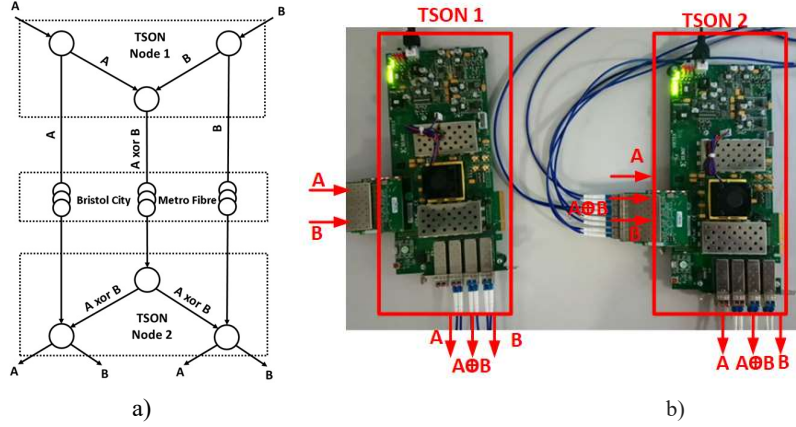
## 2 Implementation Aspects

To apply NC in 5G operational environments, two main practical aspects should be resolved: 1) implementation of the modulo-two sum and the replication operations at the FH line rate and, 2) synchronization between flows reaching decode nodes (flows  $x, x \oplus y$  and flows  $y, x \oplus y$  of Figure 1b). In the following subsections, the implementation details together with experimental demonstration of an NC-enabled optical edge node is presented.

### 2.1 NC operations implementation at TSON

TSON [13][14] is a multi-wavelength fully bi-directional synchronous, and flexible active optical transport network technology. Its network implementation consists of Field Programmable Gate Array (FPGA) optoelectronics platforms integrated with advanced optical components to enable high performance processing and transparent switching

and transport. TSON provides a multiple protocol programable interface that meets 5G Key Performance Indicators (KPIs) such as high bandwidth and sub-millisecond end-to-end latency [14]. Although natively TSON allows handling Ethernet frames, its configuration can support a broad range of framing structures and communication protocols including CPRI, either natively or through their packetized versions.

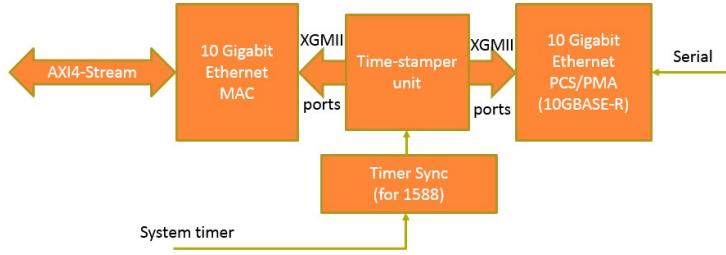


**Figure 3.** TSON Implementation architecture for evaluation concept, b) TSON edge node setup for the experimental implementation

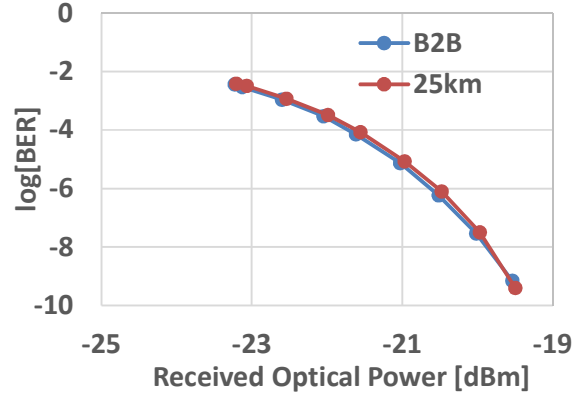
In this paper we propose the use of TSON technology to address the 5G optical transport network requirements with resilience considerations. Figure 2 shows the TSON architecture implemented to solve this problem. The ingress TSON node is responsible for traffic coding and mapping. Its ports consist of two clients: X and Y. The output ingress node contains three different wavelengths that can be configured on the fly using Software Defined Networking (SDN) to address different programmable parameters. The egress edge nodes include the reverse functionality and ports. For the implementation of our experimental configuration we have employed two Xilinx VC709 evaluation boards. These contain 4XSFP/SFP+ cages. FM-S18 modules are used to expand the number of SFP+ cages as more than 4X10Gbs ports are required for the experiment. The FM-S18 is an FPGA Mezzanine Card (FMC) module that provides up to eight SFP/SFP+ module interfaces directly into Multi-Gigabit Transceivers of the FPGA. Figure 3 shows the implementation architecture for the evaluation of the proposed concept with two TSON nodes. Each TSON node emulates three source nodes of a butterfly network, with the aim to create a proof of concept experiment and showcase the concept of linear network coding. TSON node 1 receives two different traffic streams (A and B) and sends the streams A, B, and their modulo 2 sum (XOR) of both traffic streams to TSON node 2. TSON node 2 receives the three traffic streams and transmits each traffic stream A and B simultaneously to two destinations of TSON node 2.

## 2.2 Synchronization of Network Coded flows

To reduce buffering requirements during the coding/decoding phase of the FH flows, high synchronization accuracy across the network is needed. An early TSON prototype with local synchronization capabilities is described in [11]. To address the system wide strict synchronization requirements of the NC implementation, a subsystem relying on separate developed time stamper has been developed. **Figure 4** shows the Subsystem architecture for the NC-enabled TSON nodes. The time stamper unit is located between the MAC and PCS/PMA IP cores, uses the Timer Syncs clock and follows the IEEE 1588 protocol. In addition, the time stamper considers the physical layer delay for stamping.



**Figure 4:** Synchronization subsystem for the NC implementation



**Figure 5:** BER measurements

## 2.3 Subsystem experimental validation

Two different scenarios are considered for experimental evaluation of the subsystems responsible for the NC- operations, including the modulo-two sum and synchronization accuracy. The first scenario includes both FPGAs connected back-to-back with short fibre lengths. In the second scenario, the proposed technologies are evaluated over the Bristol City test-bed Fibre with 25km of standard single-mode fibre (SSMF). An Anritsu traffic analyser generates two Ethernet traffic streams to the TSON edge node 1

at 9Gbps. The traffic is received from the TSON node 2. The performance parameters under consideration include Bit Error Rate (BER) and latency. Latency is defined as the time difference between the arrival of a frame at the analyser, and its departure from the analyser.

**Figure 5** shows the BER measurements as a function of received optical power for the different scenarios under consideration. The BER curves show that the penalty observed for the case of 25km of SSMF transmission over the Bristol City Infrastructure compared to the back-to-back (B2B) performance is less than 1dB. **Table 1** displays the end-to-end latency for the transmitted flows. The TSON nodes latency for the 25km transmission is less than 2% of total latency.

**Table 1:** End-to-end flow latency

latency	$\mu\text{s}$
B2B	1.979
25km	125.4

### 3 Optimal 5G Network design with resilience considerations

In the previous section, the implementation details of NC-enabled TSON nodes have been described. In this section, the problem of optical placement of these nodes at a metro environment to support resilient operation of C-RANs is provided.

#### 3.1 Traditional Optimization framework

This section provides a description of the modeling framework used to identify the optical network resources for the interconnection of the RUs with the compute resources where the BBU are hosted. This formulation extends the work in [1] to address resilience and protect the 5G network from a possible failure of optical and/or DC network elements. Taking into account both FH network and BBU processing demands, let  $\mathcal{P}_r$  be the set of paths interconnecting RU  $r \in \mathcal{R}$  with server  $s$  where BBUs are hosted with  $p \in \mathcal{P}_r$ . Now let  $x_{rp}$  be the rate at which FH demand originating from  $r$  flows through path  $p$ . The following demand constraints should be satisfied:

$$\sum_{s \in \mathcal{S}} \sum_{p \in \mathcal{P}_r} \alpha_{rs} x_{rp} = h_r, \quad \forall r \in \mathcal{R} \quad (1)$$

where  $\alpha_{rs}$  is a binary coefficient taking values equal to 1 if RU  $r \in \mathcal{R}$  is supported by server  $s$ .

In order to protect the planned network from a possible server failure hosting the BBU, a backup mechanism is introduced. This mechanism ensures that in case of failure of the primary server  $s$ , FH flows are routed to an alternative server  $s'$  ( $s' \neq s$ ) through the candidate path  $p'$  ( $p' \in \mathcal{P}_r$ ) with corresponding flow  $x_{rp}$ . To formulate this requirement the binary coefficient  $\alpha_{rss'}$  is introduced to indicate whether FH flow originating from RU  $r$  is assigned to servers  $s, s'$  or not. This coefficient equals to 1, if BBU

of RU  $r$  is processed at server  $s$  or in case of its failure on server  $s'$ ; 0 otherwise. In order to protect the operation of an RU from a possible server  $s$  failure, the following FH flow protection constraints should be satisfied:

$$\sum_{\substack{s', s' \neq s \\ s, s' \in \mathcal{S}}} \sum_{\substack{p' \in \mathcal{P}_r \\ p' \neq p}} \alpha_{rss'} x_{rp'} = h_r, \forall r \in \mathcal{R}, s \in \mathcal{S} \quad (2)$$

Summing all FH flows over the optical network link  $e$  ( $e \in \mathcal{E}$ ), the necessary link  $e$  capacity, denoted as  $u_e$ , is determined:

$$\sum_{r \in \mathcal{R}} \sum_{s \in \mathcal{S}} \left[ \sum_{p \in \mathcal{P}_r} \beta_{erp} x_{rp} + \sum_{\substack{s' \in \mathcal{S}, p' \in \mathcal{P}_r \\ s' \neq s}} \beta'_{erp'} x_{rp'} \right] \leq u_e, \quad \forall e \in \mathcal{E} \quad (3)$$

$$u_e \leq \mathcal{C}_e, \quad \forall e \in \mathcal{E} \quad (4)$$

In (3),  $\beta_{erp}$  and  $\beta'_{erp'}$  are binary coefficients taking values equal to 1 if link  $e$  belongs to path  $p$  and  $p'$ , respectively, realizing FH flow  $r$  at server  $s$  or  $s'$ ; 0 otherwise. In (4),  $\mathcal{C}_e$  is an upper bound of the capacity of link  $e$ .

Apart from server failures, optical network link failures are also addressed by forwarding FH flows to their destination via alternative paths. In order to protect the network from a possible link failure, a mechanism routing flows through alternative paths is introduced. Now, let  $\mathcal{Q}_{rp}$  be the set of paths that can be used to protect a path  $p \in \mathcal{P}_r$  from a possible failure,  $y_{rq}$  the rate at which FH demand originating from  $r$  flows through path  $q_p \in \mathcal{Q}_{rp}$  protecting main path  $p \in \mathcal{P}_r$  (with  $p, q$  being disjoint) and  $u'_e = \mathcal{C}_e - u_e$  the remaining link  $e$  capacity. Adopting the same rationale as in equations (1)-(4), the following path-protection constraints are introduced:

$$\sum_{s \in \mathcal{S}} \sum_{q \in \mathcal{Q}_{rp}} \alpha_{rs} y_{rq} = h_r, \quad \forall r \in \mathcal{R}, p \in \mathcal{P}_r \quad (5)$$

$$\sum_{\substack{s', s' \neq s \\ s, s' \in \mathcal{S}}} \sum_{q' \in \mathcal{Q}_{rp}} \alpha_{rss'} y_{rq'} = h_r, \forall r \in \mathcal{R}, s \in \mathcal{S}, p \in \mathcal{P}_r \quad (6)$$

$$\sum_{r \in \mathcal{R}} \sum_{s \in \mathcal{S}} \left[ \sum_{q \in \mathcal{Q}_{rp}} \beta_{erq} y_{rq} + \sum_{\substack{s' \in \mathcal{S}, q' \in \mathcal{Q}_{rp} \\ s' \neq s}} \beta'_{erq'} y_{rq'} \right] \leq u'_e, \quad \forall e \in \mathcal{E}, p \in \mathcal{P}_r \quad (7)$$

So far, the proposed model ensures that the network capacity is adequate to support the transmission of the FH flows to the servers where BBUs are hosted. However, once the information arrives at its destination, server  $s$  should have adequate capacity to support of BBU processing. To evaluate this capacity,  $h_r$  is mapped from a network type of requirement to a computing resource through the introduction of parameter  $\mathcal{M}_{rs}$ . This parameter specifies the computational requirements (usually in Instructions Per Second - IPS) to support FH flow  $r$  on server  $s$ .



To evaluate this parameter, an extensive benchmarking campaign utilizing OpenAirInterface (OAI) has been carried out. OAI is an open source software-based implementation of the LTE architecture for 5G experimentation and prototyping that encompasses the full protocol stack both in the E-UTRAN and the Evolved Packet Core (EPC) that runs in a commodity x86-based Linux Personal Computer or data center. In this system, the transceiver functionality is realized via a software radio frontend (such as the Ettus USRP B210). The combination of the open-source software and the inexpensive hardware involved, makes OAI a very attractive platform for experimentation and research towards the forthcoming 5<sup>th</sup> Generation. The platform comprises two components: *i*) openairinterface5g which implements the E-UTRAN, that is, eNodeB and UE and, *ii*) openair-cn which implements the Core Network, that is, the MME HSS, S-GW and P-GW. Based on OAI, the parameters  $\mathcal{M}_{rs}$  for various wireless access network configurations has been evaluated. The total volume of BBU processing performed at  $s$  is given by:

$$v_s(x) = \sum_{r \in \mathcal{R}} \sum_{p \in P_r} \alpha_{rs} \mathcal{M}_{rs}, \quad s \in \mathcal{S} \quad (8)$$

Besides the working capacity, a spare set of resources should be reserved at each server  $s$  for protection purposes. Servers' capacity protection constraints are expressed through

$$v'_{s'}(x) = \sum_{r \in \mathcal{R}} \sum_{p \in P_r} \sum_{\substack{s \in \mathcal{S} \\ s \neq s'}} \alpha_{rs's'} \mathcal{M}_{rs's'}, \quad s' \in \mathcal{S} \quad (9)$$

As already mentioned, the primary objective of the proposed scheme is to minimize the total power consumption of the resulting network configuration. Let  $k_e$  being the cost of the capacity of link  $e$  of the optical network and  $PC_s$  the power consumed at server  $s$ . The following cost function should be minimized:

$$\min \mathcal{O}(\boldsymbol{\rho}, \mathbf{x}) = \sum_{e \in \mathcal{E}_0} k_e(u_e(\mathbf{x}) + u'_e(\mathbf{x})) + \sum_{s \in \mathcal{S}} PC_s(v_s(\mathbf{x}) + v'_s(\mathbf{x})) \quad (10)$$

subject to constraints (1)–(9).

### 3.2 Extension: Integration of NC

In the Section 3.1, a modeling framework enabling resilient operation of the C-RAN system by protecting it from possible optical network and/or compute failure has been proposed. To address the very high bandwidth requirements that are imposed by this approach, an alternative formulation employing NC is proposed. To demonstrate the potential of NC in resilient C-RAN networks let us consider the simple 5G topology of Figure 1. Adopting the traditional approach, multiple source-destination paths must be established double-sizing the necessary network bandwidth is some parts of the optical network (i.e links interconnecting nodes 2-4, 4-5 and 4-6 in Figure 1a). This may act as bottleneck considering that in FH networks this capacity may be extremely high. The adoption of NC, however, resolves this issue as it multiplexes FH streams originating from the two RUs. At the edge, FH streams are replicated (nodes 1, 3) and transmitted through disjoint paths 1-2, 1-3. Then, at node 2 instead of forwarding protection FH

flows from regions  $x$  and  $y$ , the modulo-two sum  $x \oplus y$  is transmitted over links 2-4, 4-6 and 4-5. At the egress nodes where BBUs are connected, the operations  $x \oplus (x \oplus y)$  and  $y \oplus (x \oplus y)$ , are performed for BBU1 and BBU2, respectively, recovering FH flows  $y$  and  $x$ , respectively. Thus, by enabling encoding and decoding processes at the edge, throughput in survivable C-RAN architectures can be increased by a factor of 2.

An architectural decision in NC-enabled C-RANs is associated with the placement of the modulo-two sum and replication operations at the edge nodes. To optimize the operation of resilient NC-enabled C-RANs, equations (5)-(7) of the original problem are dropped and replaced by a suitable set of constraints enabling NC. Let  $\mathcal{N}_1$ ,  $\mathcal{N}_2$ , be the set of nodes where the modulo sum and replication operations are performed. To keep the analysis tractable, we assume that RUs are located in regions,  $x, y$ , as shown in **Figure 1b**), however, it can be easily extended to multiple nodes. Now, let  $\mathcal{R}_x, \mathcal{R}_y$  be the set of RUs belonging to regions  $x, y$ , respectively with  $\mathcal{R} = \mathcal{R}_x \cup \mathcal{R}_y$  and  $\delta_{n1}$  a binary variable taking value equal to 1 if the protection flows of RUs originating from regions  $x, y$  are multiplexed at node  $n_1 \in \mathcal{N}_1$ . The following flow constraints should be satisfied:

$$\sum_{n_1 \in \mathcal{N}_1} \sum_{q \in \mathcal{Q}_{rn_1}} \delta_{n1} y_{rq} = h_z, \quad \forall r \in \mathcal{R}_z, z = x, y \quad (11),$$

$$\sum_{r \in \mathcal{R}_x} \sum_{\substack{k \in \mathcal{R}_y, \\ k \neq r}} \sum_{n_1 \in \mathcal{N}_1} \delta_{n1} = 1 \quad (12)$$

where  $\mathcal{Q}_{rn_1}$  denotes the set of paths interconnecting an RU  $r$  with node  $n_1$ . Equation (12) indicates that the encoding process of all RUs will be performed at a single node. The encoded multiplexed stream  $y_{n1} = y_{rq} \oplus y_{kq}$  is then forwarded to node  $n_2 \in \mathcal{N}_2$  where the replication operation is performed. Flows are transmitted over candidate paths  $q \in \mathcal{Q}_{n1n2}$  interconnecting nodes  $n_1$  and  $n_2$  with capacity  $z_q$ ,  $q \in \mathcal{Q}_{n1n2}$ . Introducing the binary variable  $\gamma_{n2}$  taking value equal to 1 if the output of node  $n1$  is forwarded to node  $n2 \in \mathcal{N}_2$  or not, the following equations yields:

$$\sum_{n_2 \in \mathcal{N}_2} \sum_{q \in \mathcal{Q}_{n1n2}} \gamma_{n2} z_q = y_{n1}, \quad \forall n_1 \in \mathcal{N}_1 \quad (13)$$

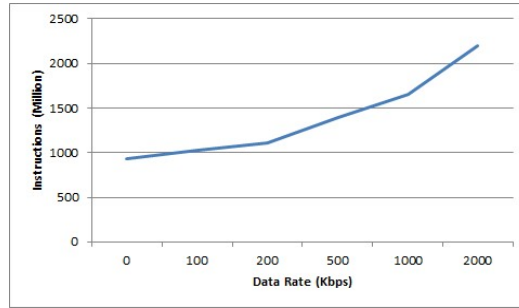
with  $\sum_{n_2 \in \mathcal{N}_2} \gamma_{n2} = 1$ .

The replicated flows  $z_q$  are then routed to the locations where BBU are hosted over the shorted available paths. Finally, taking the summation of all FH flows over the optical network link  $e$ , the necessary protection capacity at  $e$ ,  $u'_e$ , is determined adopting a similar approach to equations (3), (7). Finally, the NC-enabled C-RAN network is optimized by minimizing the cost function (10) subject to the constraints mentioned above.

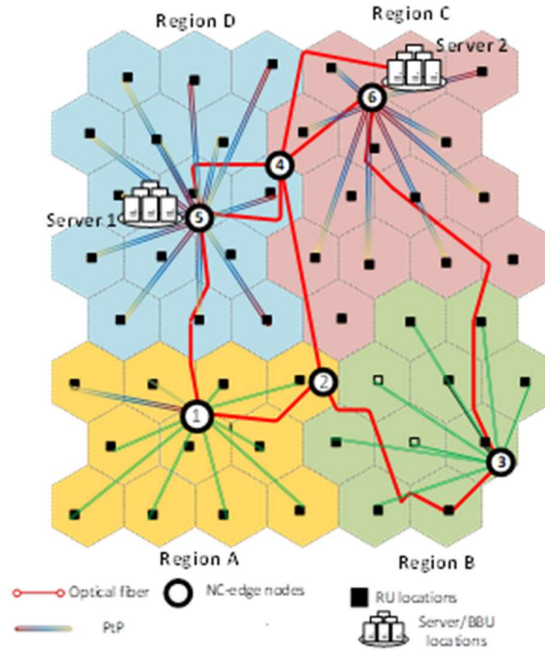
### 3.3 Network level evaluation

To evaluate the performance of the overall system, the processing requirements of the virtualized BBUs, and, consequently parameter  $\mathcal{M}_{rs}$ , are determined. To achieve this, an extensive set of experiments has been carried out using OAI. Performance analysis includes CPU Utilization and instructions' measurement for different data rates as

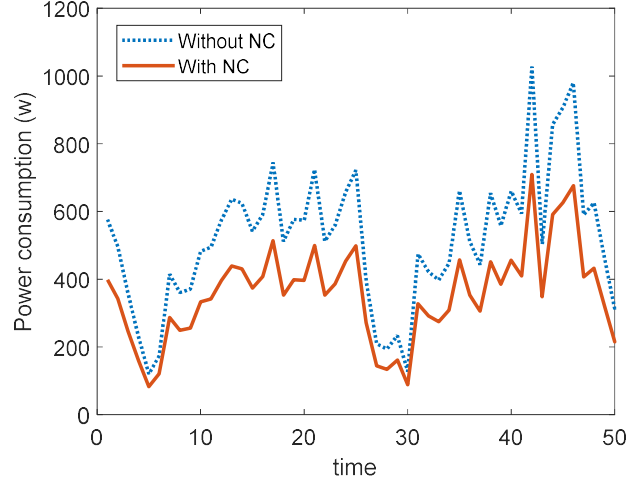
well as the application profiling. The measurements were performed with the use of the `top` command, which monitors the running processes in Linux systems and `perf` which is a collection of tools for system profiling. More specifically, the OAI profiling was done with the `record` command, which summarizes where CPU time is spent. Measurements were performed in the idle mode (LTE device phone not connected) and while downloading with different data rates (100Kbps, 200Kbps, 500Kbps, 1Mbps and 2Mbps). The results are given in Figure 6. The measurement was performed with the `perf stat` command. As we can see, the instructions are clearly increasing in proportion to the data rate.



**Figure 6.** Total instructions per second for OAI as a function of access data rate



**Figure 7.** Modified Bristol city topology with NC enabled nodes.



**Figure 8.** Bristol City Optical Network Power Consumption for the provisioning Resilient C-RAN services.

Once BBU requirements have been determined, the performance of the overall system with and without NC considerations is examined for the Bristol City topology shown in **Figure 7**. In this topology, RUs are attached to the edge node through point to point links. For this topology, BBU processing for Regions A and D will be provided by Server 1 whereas BBU processing for Regions B and C by Server 2. At the same time, the main FH connectivity will be provided through links 1-5 and 3-6 for regions A, B, respectively. Protection of FH flows will be provided through paths 1-2-4-6 for Region A, 3-2-4-5 for region B, 5-4-6 for region D and 6-4-5 for region C. The encoding (replication) processes for regions A, B will be performed at node 2 (4), while for Regions C and D decoding and replication operations will be both formed at node 4.

A comparison of the optical network power consumption for the Bristol City network for the provisioning of resilient C-RAN services is shown in **Figure 8**, with and without the adoption of NC. It is observed that when NC is adopted, the protection capacity of the optical network is reduced by approximately 33% leading to an overall reduction of the power consumption.

## 4 Conclusions

The problem of provisioning of C-RAN services over optical transport networks with resilient considerations has been studied. Recognizing the high bandwidth requirements that emerge from this type of services, a novel approach based on Network Coding (NC) has been proposed. In order to apply NC in realistic 5G network environments, execution of the modulo-2 sum and the replication operation at fronthaul line rate is required. An additional challenge relates to the very high storage capacity required at the edge of the transport network for the temporal storage of the FH flows that arrive from disjoint protection paths. In response to these challenges, a novel architectural framework and a

hardware implementation have been proposed that manage to perform NC-related operations at line rate and synchronize the FH flows arriving at the BBUs keeping buffering at the edge as low as possible. The performance of the proposed solution has been experimentally evaluated demonstrating negligible penalties. Network level modeling results demonstrate a reduction of the total optical network capacity required for this type of applications by 33%.

## 5 Acknowledgment

This work has been financially supported partially by the EU Horizon 2020 project 5G-PICTURE under grant agreement No 762057 and the EU Horizon 2020 project IN2DREAMS under grant agreement No: 777596.

## References

- [1] A. Tzanakaki *et al.*, "5G infrastructures supporting end-user and operational services: The 5G-XHaul architectural perspective," *IEEE ICC*, 2016.
- [2] M. Ruffini, Multi-Dimensional Convergence in Future 5G Networks. IEEE/OSA JLT, Vol. 35, No. 3, March 2017.
- [3] B. Khorsandi, F. Tonini, C. Raffaelli, "Design methodologies and algorithms for survivable C-RAN," *ONDM 2018*, pp. 106-111.
- [4] B. M. Khorsandi, C. Raffaelli, M. Fiorani, L. Wosinska and P. Monti, "Survivable BBU Hotel placement in a C-RAN with an Optical WDM Transport," *DRCN 2017* 2017, pp. 1-6.
- [5] M. Shehata, O. Ayoub, F. Musumeci and M. Tornatore, "Survivable BBU Placement for C-RAN over Optical Aggregation Networks," *2018 20th ICTON*, Bucharest, 2018, pp. 1-4.
- [6] S. Mohamed *et al.*, "Resilient BBU placement in 5G C-RAN over optical aggregation networks", *Photonic Network Commun.*, Jan. 2019
- [7] E. Wong, E. Grigoreva, L. Wosinska and C. M. Machuca, "Enhancing the survivability and power savings of 5G transport networks based on DWDM rings," in *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, no. 9, pp. D74-D85, Sept. 2017.
- [8] C. Colman-Meixner, G. B. Figueiredo, M. Fiorani, M. Tornatore and B. Mukherjee, "Resilient cloud network mapping with virtualized BBU placement for cloud-RAN," *in proc. of ANTS*, Bangalore, 2016, pp.
- [9] A. Tzanakaki, M. P. Anastasopoulos and D. Simeonidou, "Optical networking: An Important Enabler for 5G," *2017 European Conference on Optical Communication (ECOC)*, 2017, pp. 1-3.
- [10] T. K. Dikaliotis, A. G. Dimakis, T. Ho and M. Effros, "On the delay of network coding over line networks," *IEEE ISIT* 2009, pp. 1408-1412.
- [11] 5G-XHaul Project, Deliverable D2.2 "System Architecture Definition", submitted on July 1st, 2016.
- [12] "IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems", IEEE Std 1588-2008.
- [13] Y. Yan. *et al.*, "FPGA-based Optical Network Function Programmable Node", in *Proc. OFC* (2014)
- [14] A.-F. Beldachi. *et al.*, 'Experimental Demonstration of 5G Fronthaul and Backhaul Convergence based on FPGA-based Active Optical Transport'. *in proc of ECOC* 2018.
- [15] <http://www.ieee802.org/1/pages/tsn.html>
- [16] [https://www.xilinx.com/products/intellectual-property/axi\\_10g\\_ethernet.html](https://www.xilinx.com/products/intellectual-property/axi_10g_ethernet.html)
- [17] [https://www.xilinx.com/support/documentation/ip\\_documentation/axi\\_10g\\_ethernet/v3\\_1/pg157-axi-10g-ethernet.pdf](https://www.xilinx.com/support/documentation/ip_documentation/axi_10g_ethernet/v3_1/pg157-axi-10g-ethernet.pdf)
- [18] 5G-XHaul Project, Deliverable D3.1 "Evaluation of wireless-optical converged functionalities at UNIVBRIS testbed", June 31st, 2016